Priority-Based Traffic Scheduling and Utility Optimization for Cognitive Radio Communication Infrastructure-Based Smart Grid

Jingfang Huang, Honggang Wang, Yi Qian, and Chonggang Wang

***Abstract*—Smart grid can be visualized as an intelligent control system over sensors and communication platforms. Recently, wireless multimedia sensor networks (WMSNs) have shown its advantages for smart grid by providing rich surveillance information for grid failure detection and recovery, energy source monitoring, asset management, security, etc. On the other hand, cognitive radio (CR) networks have been identified as a key wireless technology to reduce the communication interferences and improve the bandwidth efficiency for smart grid communication. There is an essential need to use the CR communication platform to support large-size and time-sensitive multimedia delivery for future smart grid system. In this paper, we consider the heterogeneous characteristics of smart grid traffic including multimedia and propose a priority-based traffic scheduling approach for CR communication infrastructure based smart grid system according to the various traffic types of smart grid such as control commands, multimedia sensing data and meter readings. Specifically, we develop CR channel allocation and traffic scheduling schemes taking into consideration of channel switch and spectrum sensing errors, and solve a system utility optimization problem for smart grid communication system. Our solutions are demonstrated through both analyzes and simulations. This research opens a new vista of future smart grid communications.**

***Index Terms*—Cognitive radio networks (CRN), multimedia surveillance, smart grid (SG).**

I. INTRODUCTION

THE SMART GRID is an intelligent power delivery system, which utilizes the communication platform to exchange the information and optimizes the operation of interconnected power units to improve the efficiency, reliability, and sustainability of electricity services. Typically, a two-way communication infrastructure is required to exchange the real-time information between the utilities and consumers [1]. The information exchange enables many new functions and services for smart grid such as remote meter reading, control, and detection of unauthorized usage [2]. Smart grid controls intelligent appliances and diagnoses problems in consumers' houses or business buildings to reduce the energy cost and increase the system reliability, efficiency and safety [3]. It ranges from traditional central generator and/or emerging renewal distributed generator to industrial consumer and/or home users with their thermostats, electric vehicles, and intelligent appliances [4].

Wireless sensor networks (WSN) have been identified as a connected and intelligent monitoring system platform for smart grid systems. For example, low-cost wireless sensor nodes can be distributed over wild fields where the power plants are located and can enhance utility asset monitoring capabilities [4]. The control center can collect the information from remote wireless sensors to detect the behavior of the power equipment and manage the stability of the power grid. WSNs will play an important role in automatic meter reading, remote system monitoring, remote home/customer site monitoring, equipment fault diagnosing and etc. Further, wireless multimedia sensor networks (WMSNs) using sensors such as video and acoustic sensors can enhance the reliability, safety and security of smart grid system [4] by providing rich surveillance information for grid failure detection and recovery, energy source monitoring, asset management, etc. For example, using smart camera sensors for monitoring solar power plants (e.g., the light intensity and direction) can predict the amount of generated energy and thus efficiently scheduling the power distribution.

On the other hand, the application of CR technology in smart grid communications has drawn much attention due to its excellent capability to improve the spectrum usage. In addition, the application of cognitive radio network can also alleviate the burden of purchasing licensed spectrum for utility providers [5]. These advantages make cognitive radio networks a necessary component for smart grid communication infrastructure. The growing needs of multimedia sensor applications for smart grid system require wireless huge amount of bandwidth and network resources, it is critical to use the CR to support various traffic types including multimedia for future smart grid system.

A key point for the success of smart grid system is how to meet the heterogeneous communication requirements such as high reliability and low latency requirement, especially under harsh environmental conditions. Smart grid requires high quality of services (QoS) and resource efficiency as well as the system expenses and bandwidth. The communication challenge demands further research and customized solutions for smart grid applications. For example, huge data amount of system monitoring (i.e., multimedia surveillance) and power unit control commands will be delivered through the smart grid communication infrastructure, which requires high radio bandwidth, and increases the interference and competition over

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the limited and crowded radio frequency. In this paper, we proposed new traffic scheduling schemes and an optimization framework to support various smart grid traffic types, including multimedia over smart grid communication platform.

II. LITERATURE REVIEW

Smart grid brings many advantages to the consumers. In addition to effective power distributions, the functions of smart grid allow consumers to contribute their clean energy back to the grid in the near future [5]. For example, a fully-charged electrical car can provide energy to appliances at the peak hour of the day when the electricity is relatively more expensive. To support these functions, sensing and collecting data from power grid is essential. The monitoring data and meter readings need to be communicated within certain time period (30 minutes, 60 minutes, or 24 hours, etc.) for real-time control. Thus, the large volume of data traffic from countless power grid units will require high network bandwidth. Cognitive radio (CR) has offered a solution to efficiently address the stringent spectrum resource problem [11]. In [12], the authors proposed a scheme to explore multi-path diversity and allow multiple video packets to be sent from different sub-channels (SCs) to achieve the system throughput. A survey has been done on the application of CR for future generation networks [13]. Due to the advantage of CR networks, CR-based applications have gained great popularity in the research community. The emerging applications of CR for smart grid have been investigated in [6], [7]. To achieve reliable and timely information exchange in SG systems, the QoS (Quality of Services) and security aspects need to be considered. The emergence of CR network can effectively utilize the free bandwidth, as well as enhance the network security for SG [2], [8]. Particularly, the networked system state estimation in SG over CR infrastructure is studied in [1] to analyze the performance of the CR system. A sensing and delay tradeoff problem for communications in CR-enabled SG has been formulated and solved in [9]. Also, delay-sensitive multimedia transmission over CR for SG system has been studied in [10]. A CR testbed for SG is expected to be developed by the research in [8].

Various resource allocation schemes are developed to effectively manage the spectrum and link resources. In order to satisfy the target data rate and power constraints of the CR users, as well as to avoid interference of Secondary User (SU) to the existing Primary Users (PUs), a resource allocation framework in mobile ad-hoc CR networks is proposed in [14]. The resource allocation framework is carried out using multi-carrier DS CDMA modulation over a frequency-selective fading channel. A resource allocation scheme has also been proposed by the authors in [15], the algorithm of which is based on OFDM CR networks. Similar studies in [16], [17] also address channel allocation and power allocation over infrastructure based CR networks.

Based on the CR network infrastructure, a wireless sensor monitoring system can be easily deployed to form an intelligent monitoring platform. The application of wireless monitoring system in SG and the collection of multimedia content could highly improve the safety and security of the SG [12]. In [4], the application of monitoring sensors for wireless communications is introduced in order to improve the SG network monitoring capability. The application of wireless sensor networks (WSN) on smart grid system has been investigated and justified by research communities to form an intelligent monitoring platform [4], [35], [39]. WSNs will play an important role in next generation SG systems. Other recent research works in smart grid communications [36]–[38], [40] show the importance of integrating wireless communications with wireless networks for smart grid.

Further, the communication of multimedia surveillance information in CR-based SG systems requires various multimedia transmission techniques to maintain the multimedia quality. The research of multimedia transmissions over CR networks has been regarded as a cross-layer design problem. In [18], the authors proposed a cross-layer framework to effectively optimize the video quality of receivers with consideration of upper layer performance. Multi-user transmission control of scalable video content is proposed in [19] to improve the video quality. In [20], sensing period is optimized to determine the right time slots for spectrum sensing. In [21], an adaptation system is proposed to reduce the negotiation of users by adaptive transmissions over interfering CR networks. In [12], the authors proposed a technique for transmitting distributed multimedia information using fountain codes and dynamic selection of the number of cognitive radio SCs. In this paper, we consider multiple types of SG traffic and develop solutions to improve the performance of CR communication infrastructure based smart grid systems.

III. PRIORITY-BASED TRAFFIC SCHEDULING FOR SMART GRID

A. *Multimedia Communication in Smart Grid Systems*

In smart grid systems, real-time multimedia surveillance of the critical assets, substations and the household appliances is performed by the smart meters in order to observe security and network health conditions. In case of electricity outage, not only can the real-time monitoring information diagnose which asset in the smart grid system is out of work, but it can also indicate the way that asset is damaged.

Moreover, the application of smart camera in wind power plants can help monitoring the light intensity and direction so that the administrators can adjust the direction of solar panels. Video surveillance around and inside of consumers' house can provide intrusion identification and monitoring of the household appliances (e.g., TV set, audio system, oven, washer, and dryer). Overall, the video surveillance of smart meters can provide better security and visual inspection of the distributed equipment and household appliances. Accordingly, efficient multimedia transmission techniques are of most importance and essential to fulfill the duty of smart grid systems.

B. *Prioritized Network System*

To achieve effective SG communication, modern communication technologies must be able to offer multiple services and meet service requirements of heterogeneous applications. The need to prioritize the traffic types is just as important as the capability to adapt to varying network conditions in real time [22]. In smart grid applications, a typical traffic type is the control commands with small packet size [23]. In the proposed CR network for SG system, the data traffic is prioritized into three classes:

1) *The vital messages*: The vital messages are mainly for control, protection and management of the SG (e.g., notification of a sudden voltage drop, a switching command for an actuator) are classified into the highest priority for the crisis notification. This type of traffic is characterized by the message transmitted from nodes to the control center or vice versa [24]
2) *System monitoring information from sensors*: The monitoring information including multimedia surveillance is

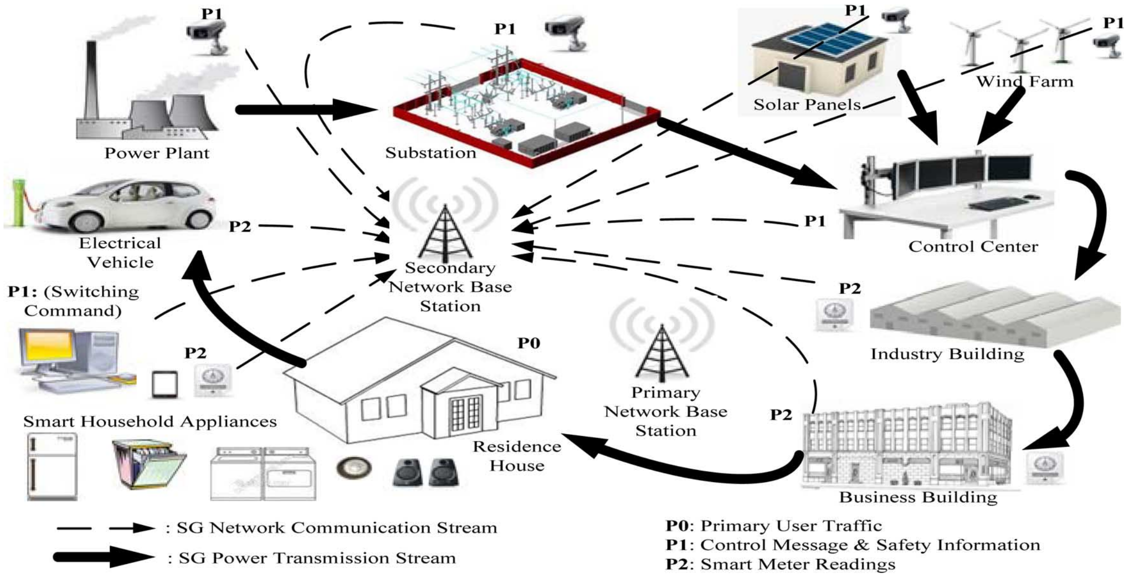


Fig. 1. System architecture for SG system, $S = 3$.

classified into the second highest priority due to the possibility that the power plant/device may be destroyed by natural disaster, severe weather or accidents such as animal damage.

3) *The meter readings*: The various meter reading is classified into the third highest priority, which is less time-sensitive and transmitted in certain time period depending on the network requirements.

C. The CR Network Architecture for SG

In our study, a spectrum band consists of P orthogonal channels with identical bandwidth. These channels are shared by P primary users (PUs) and N secondary users (SUs). The N SUs are further prioritized into S classes. As shown in Fig. 1, in this network system, all the SUs send information to the CR base station. All the users in the CR network system are categorized into $(S+1)$ priority levels, in which PU's priority level is 0 (the lower number of the users have higher priority).

In Fig. 1, the CR network architecture with three priority classes for SG is presented, where three types of traffic is illustrated as shown by P0, P1, and P2. Based on the available resources, the base station will make spectrum decision and inform each SU their available channel resource according to their priority. At each SU node, there is an information queue which buffers source packets according to the priority of a packet. While utilizing free spectrum resources, each SU should be aware of the PU reappearance and could be dropped off from this channel immediately.

In our proposed scheme, encoded packets are transmitted through selected subchannels from the spectrum pool based on quality requirement. We consider a single-hop CR network system here, which is characterized by a topology graph $\Omega(P, N)$, that has a set of PUs $P = \{p_1, p_2, \ldots, p_P\}$, a set of SU nodes $N = \{n_1, n_2, \ldots, n_N\}$, which are connected to the base station as long as the node and free channels are available at the same time. Assume the number of channels is exactly the number of PUs, which means there are P channels. There are a total of N SU nodes, which could function as source or destination nodes, and the SUs are classified into S priority classes from high to low: $(\mathrm{SU}_1, \mathrm{SU}_2, \ldots, \mathrm{SU}_S)$.

According to the priority class of SUs, the available channels are sorted according to their quality. The lower index of the SUs represents the higher access ability to the available channels. The packets of each priority of SUs are further classified into M priority classes, where M represents the importance of that packet (the lower the more important). The available resource matrix for SU priority class $\mathrm{SU_n}$ is represented by $\mathbf{R_n}$. Whether a channel is available for $\mathrm{SU_n}$ depends not only on the connectivity, but also on the interference coming from other SUs, sensing errors, and channel switching interferences. The types of interferences will be explained in detail in the next subsection.

D. Interference Characterization

For a SU node n, there are four types of interferences: interference from PUs, interference from higher priority class SUs, interference induced by channel switch, and interference caused by channel sensing errors.

1) Interference from PUs: Although the design principle of CR networks is that, the SU will be dropped off as soon as a PU reappears in the network so that the SU will cause no interference to PU, the SUs can still cause interference to PUs due to their imperfect spectrum sensing. Here, we define a spectrum opportunity matrix $\mathbf{Z_n}$ (SOM) for SU from priority class $\mathrm{SU_n}$ that is formed similarly with the one in [25]. We also assume that the spectrum opportunity matrix is available to all SUs as explained in [34].
2) Interference from Higher Priority Class SUs: In the CR networks, if a higher priority class SU occupies one available channel resource, it would cast interference for lower class SUs. The interference is defined as a channel resource matrix for $\mathrm{SU_i}$ if it is interfered by the transmission traffic from $\mathrm{SU_k}$. We define the interference matrix of SU from priority class $\mathrm{SU_k}$ as $\mathbf{I_k}$:

$$\mathbf{I_K} = [I_i] \in \{0,1\}^{1\times P}$$
$$I_t = \begin{cases} 1, & \text{if channel } i \text{ for node } n \text{ can be interfered} \\ & \text{by the SU traffic of priority class } SU_k \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

3) *Interference Caused by Channel Switch*: If the current channel of a SU is becoming unavailable before or at the end of a transmission interval because of the reappearance of a PU or a higher priority class SU, the SU will need to switch to another available channel. At each spectrum sensing phase, the SUs will observe available channels, the channel quality, and available time duration [32]. The energy left at the CR nodes potentially determines the sensing range of the node and thus the available spectrum resources. Based on the observation and energy left, the CR nodes will decide how to switch channels.

   There are two types of channel switching: periodic switching (PS) and triggered switching (TS). If PS is adopted, the SU will simply wait and switch with the notice of the next available channel; if a TS is taken, the SU will be notified for an available channel (channel that is occupied by a lower priority class SU) as soon as it loses the previous one. When TS is applied, the SU switch may cause the transmission drop of a lower priority class SU or a lower class packet, whose transmission is interfered by the higher priority class SU. If TS is adopted, more energy will be consumed as the node keeps active and waiting for available channels. So, depending on the power left of the node and the channel available probability, the action of either TS or PS is chosen carefully. Let P_T denote the probability that TS is adopted which depends on the power, and P_S denote the channel switch probability of a SU.

   In a TS mode, a SU will be informed of an available channel resource as soon as it loses the previous channel. As a result, the TS switch of a SU could cause interference to existing SUs. Assume the interference matrix caused by TS is represented by $\mathbf{SI_k}$:

$$\mathbf{SI_k} = [SI_i] \in \{0,1\}^{\times P}$$

$$SI_i = \begin{cases} 1, & \text{if } P_T P_S \succ \sigma_i\text{,channel } i \text{ for node } n \text{ can} \\ & \text{be interfered by the channle switch of} \\ & \text{priority class } SU_k \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

   in which σ_{i} represents the threshold to control the interference from a higher priority level SU. $\mathrm{P_T}$ will decrease with the decrease of the SU priority class, which indicates that the response time of higher SU class for available channel resource is shorter. $\mathrm{P_S}$ is a random number depending on the channel condition.

4) *Interference Caused by Sensing Errors*: In CR networks, if the spectrum sensing is perfect, the spectrum utilization will be significantly improved while maintaining the service quality for PU. However, the spectrum sensing in practice is not perfect due to signal attenuation, multi-path fading, limited sensing time, and limited power consumption. Sensing errors could affect the transmission quality of both PU and SU severely. Generally, the SUs don't know whether their sensing results have error or not. As a result, it is important to include sensing errors to resource allocation in order to assure the PUs' transmission quality and, at the same time, better utilize the available spectrum.

   There are two types of sensing errors: false alarm and missed detection. Let $\mathrm{H_1}$ denote the state that a CR channel is utilized by a PU; $\mathrm{H_0}$ denotes the state that a CR channel is not occupied by PU. When a SU detects the channel, there are mainly two detection errors:

   a) *False alarm*: the CR channel is detected as busy while it is free $\{\mathrm{H_1}|\mathrm{H_0}\}$
   b) *Missed detection*: the CR channel is detected as free while it is actually occupied by $\mathrm{PU}\{\mathrm{H_0}|\mathrm{H_1}\}$

   Let P_f denotes the probability of false alarm and P_m denotes the probability of missed detection. P_f and P_m can be calculated according to [26]. False alarm does not affect the system performance, but lowers potential spectrum utility; missed detection will result in a collision of PU and SU, thus causes interference to primary networks and affect the system performance. The level of missed detection and false alarm error could be detected by a Neyman-Pearson (NP) detector [28]. Basically, the spectrum sensing problem can be treated as a comparison of the received signal to an error detection threshold τ, which is obtained from the constraint on false alarm and missed detection probability. While false alarm does not cast interference to the existing users, missed detection can cause data collision of PU and SU, and thus interrupt the normal transmission of the CR network. In our proposed system, the sensing error from priority class SU_k is defined as $\mathbf{SR_k}$:

$$\mathbf{SR_k} = [SR_i] \in \{0,1\}^{1\times P}$$

$$SR_i = \begin{cases} 1, & \text{if } P_m \succ \tau_i \text{ missed detection happens} \\ & \text{in the sensing result of node } n \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

   where τ_{i} represents the missed detection interference threshold.

5) *The Available Resource Matrix*: The available resource matrix can then be obtained through information exchange among the neighbor nodes. For SU node n, its available resource $\mathbf{R_n^{m,k}}$ is obtained using the four types of interference matrix to mask the resource matrix of SU node n[25]:

$$\begin{aligned} \mathbf{R_n^{m,k}} = \mathbf{R_n} \otimes \overline{\mathbf{Z_n}} \otimes \overline{\mathbf{I_{k-1}}} \otimes \cdots \otimes \overline{\mathbf{I_1}} \otimes \overline{\mathbf{SI_{k-1}}} \\ \otimes \cdots \otimes \overline{\mathbf{SI_1}} \otimes \overline{\mathbf{SR^m_{k-1}}} \otimes \cdots \otimes \overline{\mathbf{SR^m_1}} \end{aligned} \tag{4}$$

   where $\otimes$ represents the element-wise multiplication of the matrices, I denotes the inverse operation of $\mathbf{I}$, where 1 turns to 0 and 0 turns to 1. This matrix represents the available resource for node n in SU priority class $\mathrm{SU_k}$ and packet class m.

IV. QUALITY AND SYSTEM UTILIZATION CONTROL FOR CR BASED SG SYSTEM

It is challenging for multimedia transmission over wireless networks to meet QoS requirements (e.g., bandwidth, delay, and quality requirements) [29]. Managing the QoS of video streaming for wireless users is becoming increasingly important in smart grid communications systems owing to the rapid growth of video traffic on wireless networks [30]. QoS not only concerns about the effective multimedia quality but also the way the users perceive the overall values of the service in terms of mobility, security, cost, suitableness, flexibility etc. For example, the dropping probability and blocking probability of SUs can be adopted to evaluate the QoS of CR network system since the termination of a user will affect the user-perceived quality.

A. Multimedia Quality Modeling

The distortion of given multimedia information that will affect its quality includes two parts: source coding distortion, and transmission distortion. At the source coding unit, the source information will be encoded by the correlation of this information to compress the data. The spatial and temporal level of the source packet should be set in order to obtain optimal source coding rate and transmission rate. While source coding reduces transmission load and promises decoding quality, it also brings source distortion. On the other hand, when the source packets are transmitted on the wireless channel, it subjects to various distortions due to the unstable wireless environment. In this paper, the transmission distortion is studied.

Because different priority class of SUs will be allocated frequency channel of different qualities, the received packets' quality will be affected by the priority class of the SU it belongs to, as well as its own priority class. The application of SU from priority class $\mathrm{SU_i}$ is Ω_{i}: $\{\Omega_1, \Omega_2, \ldots, \Omega_{\mathrm{M}}\}$, where M represents the total number of the packets' priority classes.

The quality of a frame could be evaluated considering two circumstances: 1) the packet is lost with packet loss probability $\mathrm{P_{loss}}$; 2) The packet transmission is successful and the packet is not lost $(\mathrm{P_{success}} = 1 - \mathrm{P_{loss}})$. The packet transmitted in the CR system could be lost due to four reasons as explained before:

a) Packet error with packet error rate P_e;
b) Interference by channel switch with probability of $P_T \cdot P_S$;
c) Interference by sensing errors probability: P_m;
d) The probability that the packet transmission exceeds the delay bound $P_{delay} = \Pr\{d_{ij} \geq D_{ij}\}$

Thus, the packet loss probability is:

$$\mathrm{P}_{loss} = 1 - (1 - P_e) \cdot (1 - P_T \cdot P_S) \cdot (1 - P_m) \cdot (1 - P_{delay}). \tag{5}$$

In a real transmission environment, the packet would either be lost or transmitted successfully. As a result, the total quality of the frame is calculated through two steps:

1) *Distortion Reduction of the Frame Due to Successful Packet Transmission*: Under the situation that a packet is transmitted successfully, the distortion reduction added by this packet at the receiving site only contains source coding distortion $(\mathrm{D_{source}})$, which is obtained by calculating the PSNR of the frame with decoding all the other packets losslessly, and decoding this packet at its source coding rate.
2) *Distortion Reduction of the Frame Caused by the Lost Packets*: The expected distortion reduction from lost packets is obtained by calculating the PSNR of the frame with decoding all the other packets losslessly, and this packet abandoned:

$$E_{loss}\left[\Delta D_s(V_s)\right] = \sum_{i=1}^{N_s} \left(\sum_{j=1}^{i} d_j^s\left(r_j^s\right) \right) \prod_i \left(1 - P_{\mathrm{loss i}}\right) P_{\mathrm{loss(i+1)}}. \tag{6}$$

B. CR System Utilization for SG

1) *Primary User Arrival Model*: In [31], a Markov chain analysis for spectrum access in licensed bands for CR networks is introduced. If the transmission over one SC is interrupted, the video packets over that SC would be lost. In this situation, SU has to send back a failure notice to the sender and request for retransmission. However, in CR systems, we choose LDPC error-correcting coding method to handle transmitted bit errors and thus reduce retransmission. For the SU, we consider a compressed video transmission application, which consists of a group of pictures (GOP). At the beginning of the GOP transmission, a SU link is set up by first sensing the available SCs and then choosing appropriate SCs based on their channel quality. Afterwards, the transmission will start on this link. The PU is modeled as Markov Chain process, with PU arrival rate of λ_{j} for the ith PU channel. As a result, the inter-arrival time follows exponential distribution with mean-arrival time $\mu_{\mathrm{j}} = 1/\lambda_{\mathrm{j}}$. When a PU reappears on the SC being used by the SU, the transmission on that SC will be regarded as a total loss. In other words, the transmission is successful only if completed during the inter-arrival time μ_{j} of a $\mathrm{PU_j}$.
2) *Secondary User Arrival Model*: Considering that the arrival number of applications determines the arrival traffic of a SU, the arrival rate of a SU can be derived given source coding information. The arrival rate of SUs relates to source coding mechanism of the application, where source information bits are encoded using source coding rate r_{s_i}. Assume that the number of source bits for an application from $\mathrm{SU_i}$ is a constant $\mathrm{B_i}$, the source coding rate r_{S_i} determines the number of source packets generated in certain time duration T_{Si}, which is the arrival rate of $\mathrm{SU_i}$:

$$\lambda_i = \frac{B_i}{r_{S_i} T_{S_i}}. \tag{7}$$

Hence, the arrival rate of the SU is obtained with knowledge of the application information (the source coding time duration, source coding rate, application size). Consequently, by adjusting the source coding parameters, the SU arrival rate can be regulated in order to obtain better video quality under certain channel condition. For simplicity, the SUs are modeled as Poisson process with each priority class has an user arrival rate of $\lambda_i (i = 0, 1, \ldots, S)$.
3) System Utilization Model: For this CR system, the priority of the SUs determines their access right to the CR channels. As a result, the available channel resources (server of the Markov model) for each priority class of SUs are different. Assume that the number of SUs from different priority classes $(\mathrm{SU_1}, \mathrm{SU_2}, \ldots, \mathrm{SU_S})$ are $(\mathrm{C_1}, \mathrm{C_2}, \ldots, \mathrm{C_S})$, respectively, where $\mathrm{C_1} > \mathrm{C_2} > \cdots > \mathrm{C_S}$. The reason why higher priority class SUs always has more available channel resource is that higher priority classes SUs have access to the channel of lower priority class SUs. Thus, for the $\mathrm{SU_i}$ priority class which is a $\mathrm{M \backslash M \backslash C_i}$ system, its server utilization (system utilization) is defined as [33]:

$$\rho_{\mathrm{i}} = \frac{\lambda_{\mathrm{i}}^{eff}}{(\mathrm{c_i} \cdot \mu_{\mathrm{i}})} \tag{8}$$

where $\mathrm{c_i}$ is the number of servers (number of SUs) for priority class $\mathrm{SU_i}$, μ_{i} denotes the system service rate for priority class $\mathrm{SU_i}$, λ_i^{eff} is the effective SU arrival rate from priority class $i (\mathrm{i} = 1, 2, \ldots, S)$. λ_i^{eff} is calculated on condition that the arrival of SUs satisfies the following three requirements:

a) The SU is not blocked;
b) There is no false alarm when the SU arrives;
c) The packets from this SU priority class are not lost.

Thus, the effective arrival rate of SU from priority class $\mathrm{SU_i}$ is denoted as:

$$\lambda_{\mathrm{i}}^{eff} = \lambda_{\mathrm{i}}\left(1-P_i^B\right)\left(1-P_f\right)\prod_{\mathrm{j}=1}^{\mathrm{S}}\left(1-\mathrm{P}_{\mathrm{loss_i}}^{\mathrm{j}}\right) \tag{9}$$

where P_i^B is the blocking probability of SUs from priority class $\mathrm{SU_i}$, $P_{loss_i}^j$ denotes the probability that the packet from packet priority class $\mathrm{M_j}$ and SU priority class $\mathrm{SU_i}$ is not lost. Here, j starts from 1 since the PUs occupied priority class 0.

C. System Utilization Optimization

Optimizing smart grid operations and assets is imperative. Since optimization of throughput, reliability, and delay often pose conflicting demands, the optimization of smart grid operations is a nontrivial task. To balance the diversity of variables and tradeoffs, the smart grid is expected to be optimized in terms of multiple metrics such as effectiveness and accuracy of data and communications, fault management, and time response.

In this paper, we formulate an optimization problem to obtain the best CR network channel resource selection scheme by optimizing the system utilization of all the priority class SUs, while considering system latency constraint and quality requirement. The optimization problem is formed as follows:

$$\mathrm{A^{opt}} = \arg\max\left(\omega_1\rho_1 + \omega_1\rho_2 + \cdots + \omega_S\rho_S\right) \tag{10}$$

where $\omega_1, \omega_2, \ldots, \omega_{\mathrm{S}}$ denotes the weight of each priority class SUs. ω_{i} could be tuned according to the system requirement, i.e., which priority class SUs plays more important role for the current SG system communication.

Due to the limited wireless network resource and the complexity of this optimization problem, the end to end delay constrain in parameter P_{loss}^j can make the optimization solution infeasible [31]. As a result, the optimization problem is decomposed into a sub-optimization problem that can be performed from high priority class to low priority class SUs in order to maximize system utilization ρ_{i}. Hence, for priority class $\mathrm{SU_i}$ under quality constraint, we form the optimization problem as follows:

$$\begin{aligned} \mathrm{A_i^{opt}} &= \arg\max \rho_i. \\ \text{s.t.} \quad & E\left[\Delta D_S\left(V_S\right)\right] \geq \zeta \end{aligned} \tag{11}$$

where ζ is the quality threshold defined by the QoS requirement of the smart grid application.

V. PERFORMANCE ANALYSIS AND EVALUATION

A. Performance Analysis

1) *Optimization Algorithm*: With the available resource and the interference matrix, the available resource matrix for each node will be obtained. Under the chosen channels and their PSNR values, the channel selection scheme will be optimized under the assumption that higher priority traffic has access to channel resource of lower priority SUs. In this research, we choose Genetic Algorithm (GA) as an optimization tool. The output of the optimization problem for priority class $\mathrm{SU_n}$ would be optimal system utilization ρ_n^{opt} and optimal channel selection strategy A_n^{opt}. The pseudo code in Table II shows the procedure of GA algorithm that solves the optimization problem of traffic scheduling among SUs. During the optimization process, higher priority classes of SUs have privileges to choose available spectrum resources.

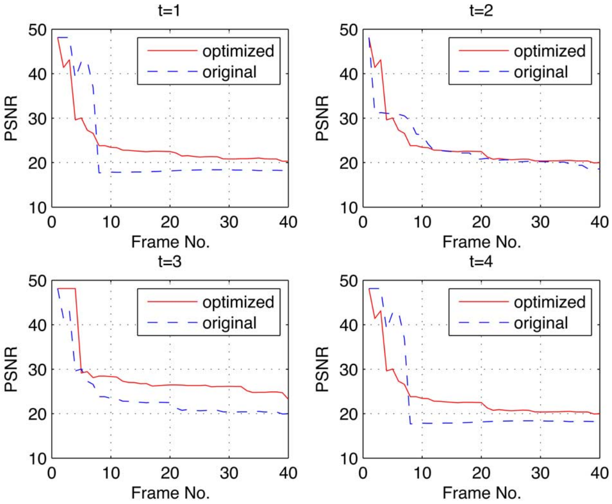


Fig. 2. Multimedia quality comparison before and after optimization.

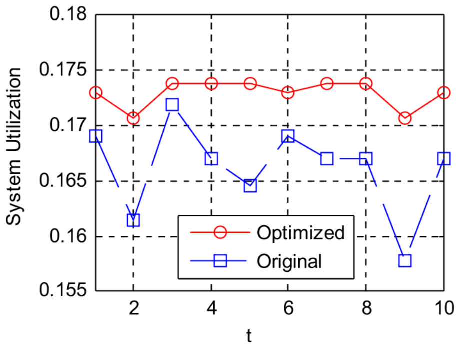


Fig. 3. System utilization comparison before and after optimization.

2) *Multimedia Quality*: Fig. 2 shows the received multimedia quality at different moments. The red line denotes received multimedia quality after adopting the proposed optimal approach (optimal dynamic channel selections). The blue dotted line shows the received multimedia quality without the optimization (fixed channel selections). The experiment is conducted based on the same video segments (40 frames of each segment) under different channel conditions. It shows that the average multimedia quality is improved after a slow start (after about 10^{th} frames) using optimal channel selection. The PSNR evaluation in the figure is for highest priority SUs. The results demonstrated that the SU with higher priority trafffic can be offered a better service.

3) *CR Network System Utilization for SG*: The advantages of the proposed optimal channel allocation are also shown in Fig. 3. It shows the system utilization comparison before and after adopting the optimization algorithm for optimal channel selection for SUs. The system utilization for the SUs is improved significantly by applying the optimal channel selection scheme.

TABLE I
SYMBOLS AND NOTATIONS

Symbols	Notations
$P=\{p_1, p_2, \ldots, p_P\}$	The number of PUs
$N=\{n_1, n_2, \ldots, n_N\}$	The number of SUs
$\mathbf{R_n}$	The available resource matrix for SU priority class SU_n
$\mathbf{Z_n}$	The spectrum opportunity matrix (SOM) for SU priority class SU_n
$\mathbf{I_k}$	The interference matrix of SU from priority class SU_k
$\mathbf{SI_k}$	The interference matrix of SU_k caused by TS
$\mathbf{SR_k}$	The sensing error from priority class SU_k
$\mathbf{R_n^{m,k}}$	The available resource matrix for SU node n from SU priority calss SU_k and packet class *m*
P_{loss}	The packet loss rate
P_f	The false alarm rate
P_m	The miss detection rate
$d_j^s\left(r_j^s\right)$	The distortion reduction of source packet *j*
A^{opt}	The optimal resource allocation scheme
ρ_i	The system utilization for SUs from priority class SU_i
P_i^B	The blocking probability of SUs from priority class SU_i

TABLE II
OPTIMIZATION PROCESS IN PSEUDO CODE

```
For n=1:$S$
  {Obtain initial system parameters: $\mathbf{R_n}$, $\mathbf{Z_n}$, $\mathbf{I_k}$, $\mathbf{SI_k}$, $\mathbf{SR_k}$.
  Calculate available resource matrix for $SU_n$: $\mathbf{R_n^{m,k}}$.
  Calculate $P_{delay}$, $P_{loss}$, and $\lambda_n^{eff}$ to obtain $\rho_n$.
  Optimize $\rho_n$ using GA:
    GA Optimization Input:
    <Chromosome>=<Available channel resource Vector: {$CS_n$}.>
    <Fitness Function>=<$\rho_n = \lambda_n^{eff}/(c_n*\mu_n)$, where $n$ denotes the priority class of the SU.>
    <Constraint>=<$E[\Delta D_S(V_S)] \geq \zeta$.>
    GA Optimization Output:
          An optimal individual: $A_n^{opt}$.
          Optimal CR System Utilization: $\rho_n^{opt}$ (fitness value of the optimal individual). }
```

B. Performance Evaluation

1) *Performance Metrics*: Assume that all the nodes in CR networks under consideration are homogeneous, i.e., statistically identical and independent. Let $N_1(t)$, $N_2(t)$, and $N_3(t)$ be random variables denoting the number of PUs, SU1s, and SU2s in the system. The process $(N_1(t), N_2(t), N_3(t))$ is a three-dimensional Markov process with state space $S = \{(i,j,k)|0 \leq i \leq N_p, 0 \leq j \leq N_p + N_{S1}+N_{S2}, 0 \leq k \leq N_{S2}\}$, where N_p, N_{S1} and N_{S2} represent the number of primary channels (PCs), number of channels for SU1s (SC1), and SU2s (SC2), respectively.

When the PCs are all occupied by PUs, the next PU will be blocked. Also, when both PC and SC1 are full, the next PU could be blocked if no miss alarm happens. The blocking probability of the PUs for this 3-D Markov model is shown as follows:

$$P_p^b = \sum_{j=0}^{N_{S1}-1}\sum_{k=0}^{N_{S2}} P_{N_p,j,k} + (1-P_m)\sum_{k=0}^{N_{S2}} P_{N_p,N_{S1},k} \qquad (12)$$

where $P_{i,j,k}$ represents the state probability that there are i PUs, j SU1s, and k SU2s in the system.

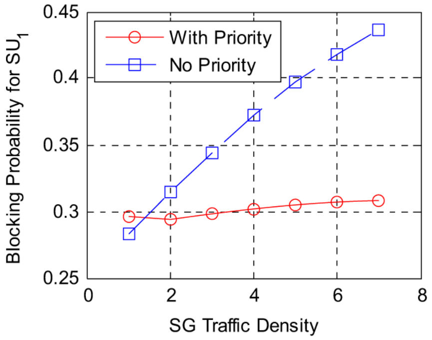


Fig. 4. Blocking probability of the SG traffic.

Under given assumptions, SU1 will be blocked under three conditions: 1) All the PCs, SC1s and SC2s are occupied by PUs and SU1s; 2) there are N_{S1} SU1s and N_P PUs in the system, and a miss detection of PU event happens; 3) there are $(N_P - 1)$ PUs and $(N_{S1} + N_{S2})$ SU1s in the system, and a false alarm event happens. SU2 will be blocked simply when the system is full. For example, the blocking probability of SU2 is shown in the following:

$$P_{S2}^b = \sum_{i=0}^{N_P}\sum_{j'=0}^{N_{S1}}\sum_{k=0}^{N_{S2}} P_{i,j,k} \qquad (13)$$

in which $j = j' + N_{S2} - k$.

The dropping probabilities for PUs, SU1s, and SU2s are defined as the total force drop rate divided by the total connection rate. PUs will be forced to drop when there is miss detection, and a collision happened between a SU1 and a PU. SU1s will be dropped when a SU1 is utilizing PC and a PU reappeared for this PC. SU2 will be dropped when 1) a SU1 claimed the SU2's channel; 2) when false alarm happens, a SU1 claimed the SU2's channel. The dropping probability of PU and SU1 are shown in the following equations:

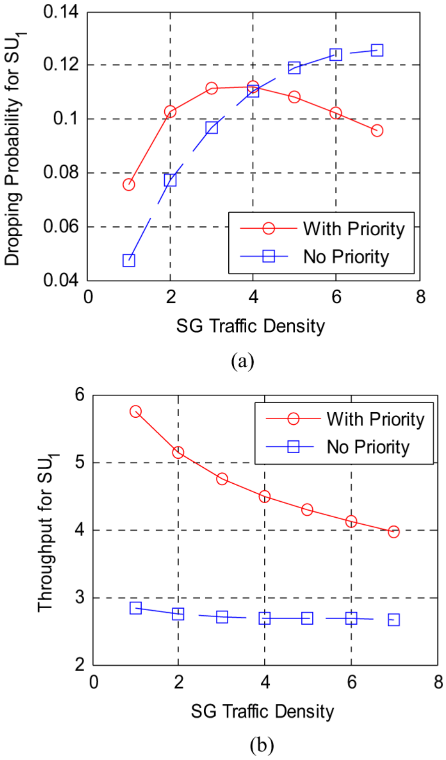
$$P_p^d = \frac{\lambda_2 P_m \sum_{k=0}^{N_{S2}} P_{N_P,N_{S1},k}}{\left(1-P_p^b\right)\lambda_1} \qquad (14)$$

$$P_{S1}^d = \frac{\lambda_1 \sum_{N_P+N_{S1}\leq i+j\leq N_P+N_{S1}+N_{S2}} P_{N_P-1,j,k}}{\left(1-P_{S1}^b\right)\lambda_2}. \qquad (15)$$

For the throughput of SUs, T is defined as the average number of service completions for SU1s and SU2s per second, respectively.

2) *Results*: Fig. 4 shows the blocking probability of the SU traffic for SG system in prioritized network system and non-prioritized system, respectively. The blocking probabilities for both network types increase with growing traffic density. However, SU1's blocking probability of the prioritized system is only increased slightly because SU1 is the highest priority secondary user and it can grab the channel resources of lower priority users instead of being blocked. On the other hand, the blocking probability of SUs in the non-prioritized system increases more largely.

Fig. 5(a) shows the dropping probability of SU1 in a CR system with or without priority settings. While the dropping



(a)

(b)

Fig. 5. (a) Throughput of the SUs over SG system. (b) The dropping probability of the SG Traffic.

probability of a system without priority setup increases largely, the dropping probability of a prioritized network system first increases due to the increase of PU, then decreases since the SU1's turn to use the channel resources of lower priority class SUs.

Fig. 5(b) shows the comparison of SU1's throughput in a CR network system with and without priority control respectively. The throughput of SU1, which is the highest priority SU traffic in SG system, is much higher than that of a system without priority control. The throughput of a system without priority control decreases slightly since its throughput depends mainly on the available channel resource instead of the traffic density. On the other hand, the SU1s' throughputs of a prioritized system decrease faster due to the influence of increasing false alarm and miss detection events.

VI. CONCLUSION

In this paper, we have investigated the application of CR network on SG systems. The different traffic types in SG are classified and prioritized for traffic scheduling of the SUs in a CR network system. An SG communication system utility optimization problem has been formulated to obtain the optimal SG communication resource utilization through choosing the optimal CR network channel selection strategy. On the other hand, the performances of a CR network system with or without priority control for smart grid communications have been also studied in the paper. It is observed that the prioritized system is more superior than a system where all types of traffic are treated the same in terms of SG traffic delivery. The research in this paper opens a new vista of future smart grid communications and has great potential in enhancing the flexibility and adaptability, and reliability of SG system.

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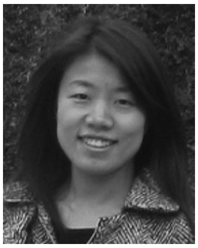

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